# AEROGEL-BASED INSULATION MATERIALS FOR CRYOGENIC APPLICATIONS

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James E. Fesmire

NASA Kennedy Space Center
Cryogenics Test Laboratory
KSC, FL 32899 USA

# HIGHLIGHTS

- Different aerogel-based materials are now used in thermal insulation systems for cryogenic applications:
  - Flexible composite blankets, bulk-fill particles, and polymer composites
  - Designed for vacuum and/or non-vacuum environments
- In ambient environments, aerogels provide superior thermal performance while offering unique advantages in solving problems with weathering, moisture, and mechanical damage
- Aerogels are also used in multilayer approaches:
  - Layered composite insulation systems are providing combined structural-thermal capability for cryogenic systems in both vacuum-jacketed and externally-applied designs
- Cryostat test data include a wide range of both commercial and experimental aerogel materials
- Examples of aerogel-based insulation systems are provided

# INTRODUCTION

- Are aerogels the answer to all insulation problems? Maybe.
- What is the best insulation material? Aerogel blanket, of course; but this is a really poor *question. Three main limitations on the use of MLI systems are summarized as follows:
    1. High vacuum is required for operation (and in the first place, it is not possible to vacuum-jacket all hardware)
    2. Not all hardware can be suitably wrapped or properly covered
    3. Localized compression will ruin the thermal performance; MLI cannot withstand mechanical loading
- Compared to the no load condition for six different MLI systems tested (average heat flux of 0.6 $W/m^2$):
    - A mere 0.7 kPa (0.1 psi) load will cause15x increase in heat flux
    - A small 7-kPa (1 psi) load will cause an approximate 40x increase
    - A modest 70-kPa (10 psi) load will cause a more than 100x increase

*The heat leak through the rendered system is what matters

# INSULATION SYSTEM DESIGN



- For a given cryogenic application, how to choose among MLI, bulk-fill, foams, aerogels, aerogel blankets, polyimide-aerogels, aerogel-foam composites, layered composites, or some combination?
- The design choice depends on four main factors:
  1. Heat load requirement (What is the problem?); cryogen and temperature range
  2. Physical design of system
  3. Installation build process
  4. Operational and maintenance requirements
- In ambient pressure applications, an alternative to closed-cell foam is the aerogel-based layered composite extreme (LCX) system:
  - LCX is "MLI for open-air" environments: unique benefits where complex shapes, weathering, moisture, and mechanical damage are problematic
  - Breathable (non-sealed) system proven at 20 K on LH2 systems: hydrophobic, nano-porous characteristics of the aerogel material
- Aerogel blanket material Pyrogel® provides high temperature capability to 923 K (1200 °F) where fire protection might be needed for cryofuel systems

# AEROGEL COMPOSITE BLANKET

Silica aerogel with fiber matrix reinforcement: Cryogel®, Spaceloft® and Pyrogel® by Aspen Aerogels, Inc.

# AEROGEL PARTICLES

Silica aerogel particles: P100, P200 and P300 by Cabot Corp.

# LAYERED COMPOSITE EXTREME (LCX)

Custom layered solutions for non-vacuum applications: *MLI systems for the open-air environment by* Xtremes LLC

# PHYSICAL PROPERTIES OF AEROGEL-BASED TEST SPECIMENS

| Cryostat | Test Series | Test Specimen | No. of Layers | Total Thickness* (mm) | Density* (kg/m³) |
|---|---|---|---|---|---|
| C100 | A108 | Bulk-fill aerogel beads | 1 | 25 | 80 |
| C100 | A111 | Pyrogel® aerogel blanket (black) | 6 | 18 | 125 |
| C100 | A194 | Cyrogel® aerogel blanket | 2 | 20 | 130 |
| C500 | G2-109 | Spaceloft® Subsea (grey) | 4 | 20 | 152 |
| C500 | G1-190 | ULD^ aerogel blanket white | 8 | 23 | 55 |
| C500 | G2-113 | ULD^ melamine flexible aerogel grey | 8 | 21 | 65 |
| C500 | G1-191 | ULD^ Aerogel MLI layered composite | 8 | 23 | 52 |
| C100 | A193 | Aerogel MLI layered composite (0.7-mm aerogel paper) | 7 | 5 | 91 |

Notes: *As tested ^Ultra-Low Density (ULD)

# PHYSICAL PROPERTIES OF ADDITIONAL INSULATION TEST SPECIMENS FOR COMPARISON

| Cryostat | Test Series | Test Specimen | No. of Layers | Total Thickness* (mm) | Density* (kg/m$^3$) |
|---|---|---|---|---|---|
| C100 | A114 | Vacuum Only (black surfaces) | 1 | 25 | n/a |
| C500 | G1-157 | SOFI Foam BX-265 | 1 | 25 | 42 |
| C100 | A102 | Glass Bubbles K1 | 1 | 25 | 65 |
| C100 | various | Kaganer Line (MLI Baseline); average of 26 different MLI test specimens | 10 - 80 | ~22 typical | ~50 typical |

Note: *As tested

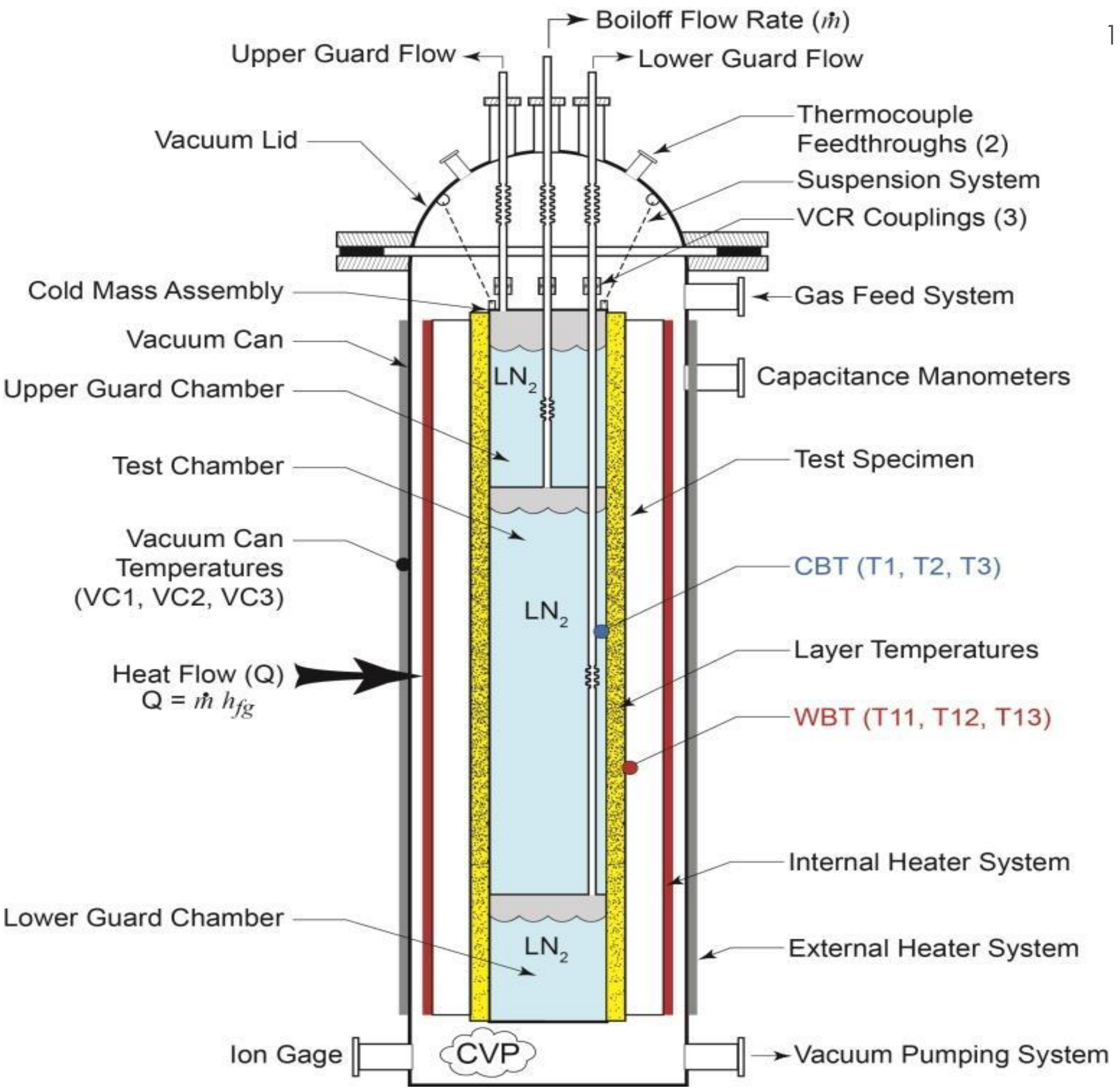
## MAIN FEATURES

- Boundary temp range: 78 K to 353 K
- Effective thermal conductivity ($k_e$) and heat flux (q)
- 1-m tall by 167-mm dia. cold mass
- Specimen thickness from 0 - 50 mm
- Guard chambers top & bottom

# CRYOSTAT-100

Cylindrical boiloff calorimeter (absolute heat flow)

ASTM C1774, Annex A1



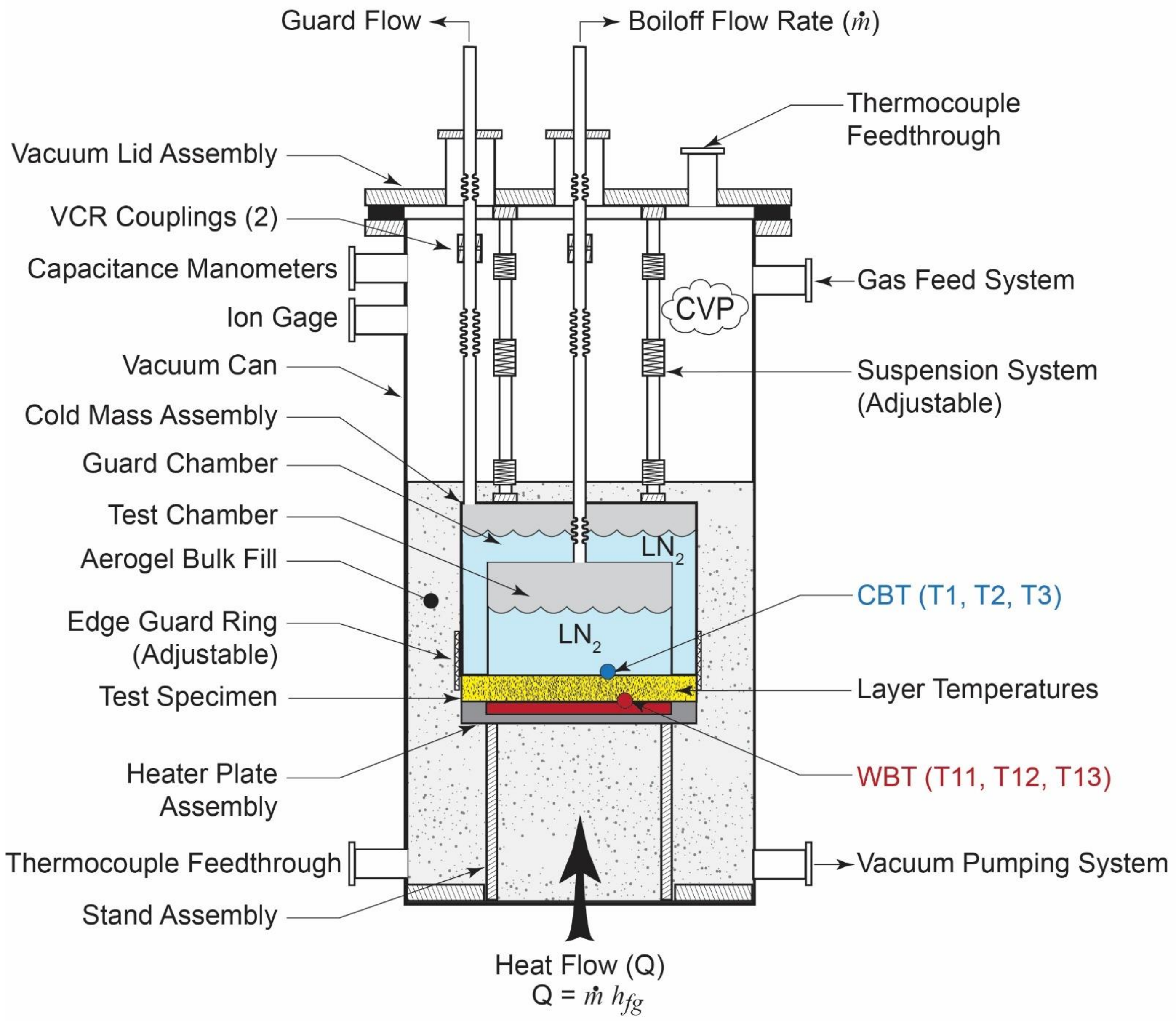
## MAIN FEATURES

- Boundary temp range: 78 K to 403 K
- Effective thermal conductivity ($k_e$) and heat flux (q)
- 204-mm diameter cold mass
- Specimen thickness from 2 - 40 mm
- Guarded test chamber

# CRYOSTAT-500

Flat Plate boiloff calorimeter (absolute heat flow)

ASTM C1774, Annex A3



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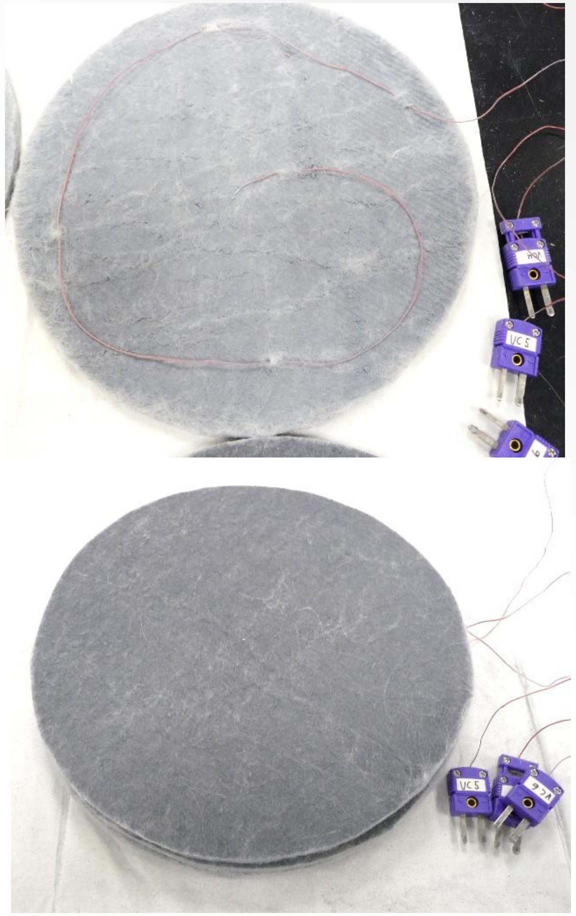
# C500 TEST SPECIMEN PREPARATION

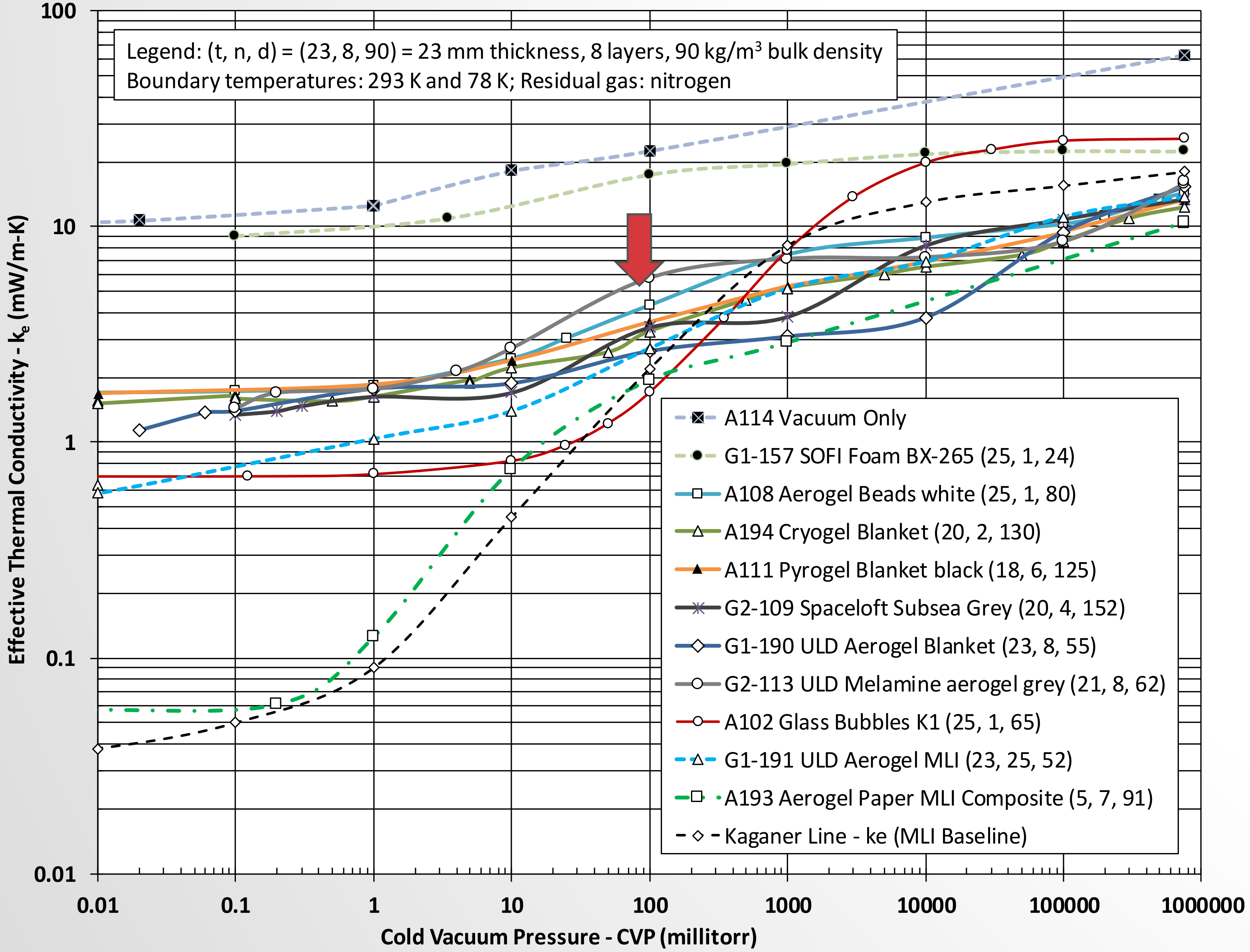
- Heating and evacuated according to standard laboratory procedures (typical):
  - Heating to ~323 K in conjunction with evacuation and gaseous nitrogen purge cycles (a minimum of three times)
  - Followed by at least 48 hours of continuous vacuum pumping
- Intermediate temperature sensors for determining the temperature dependence of thermal conductivity:
  - Three Type E, 30 gage thermocouples are placed within the specimen at specific intervals through the thickness
  - Interlayer thermal conductivity values ($\lambda$) can be calculated and reported with the mean temperature ($T_m$) for each layer
    - Up to 9 $\lambda$ points can be calculated in addition to the $k_e$ for the full $\Delta T$



G2-109 Spaceloft Subsea (Grey) preparation showing temperature sensor installation

# CRYOSTAT DATA FOR AEROGEL MATERIALS IN COMPARISON WITH A VARIETY OF OTHER CRYOGENIC INSULATION SYSTEMS






- Boiloff calorimetry
  - Cryostat-100 (A-series)
  - Cryostat-500 (G-series)
- Variation of $k_e$ with CVP
  - Boundary temperatures: 293 K / 78 K
  - Residual gas: nitrogen
- Legend: (t, n, d) where:
  - t = thickness (mm)
  - n = number of layers
  - d = bulk density (kg/m3)



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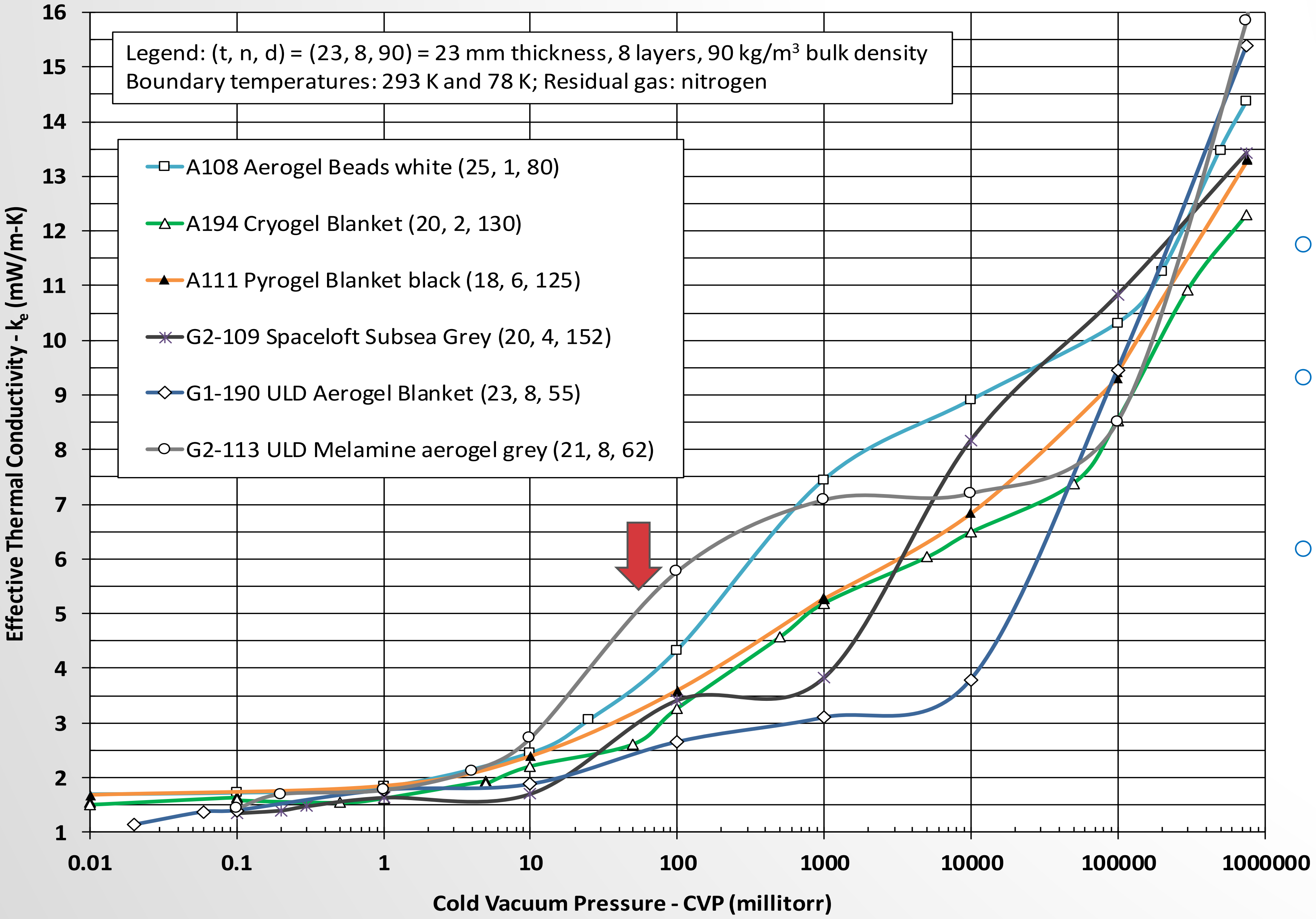
# CRYOSTAT DATA FOR AEROGEL MATERIALS



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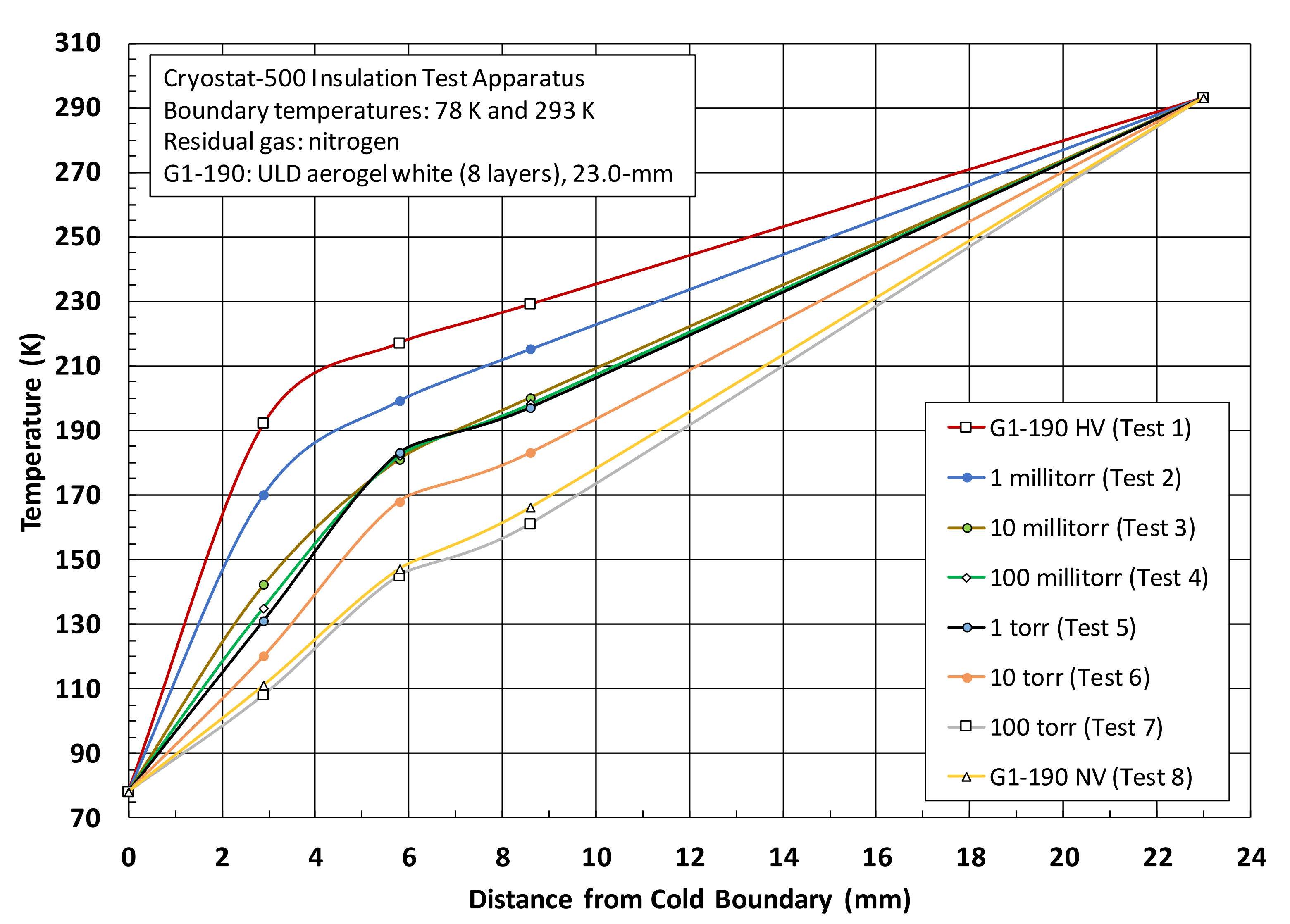
# LAYER TEMPERATURE PROFILE: EXAMPLE FROM CRYOSTAT-500 TEST SERIES






- Layer temperature profiles for G1-190 ULD aerogel white for all cold vacuum pressures:
  - From high vacuum (HV) to no vacuum (NV)
  - Three interlayer temperature sensors as indicated by the line markers

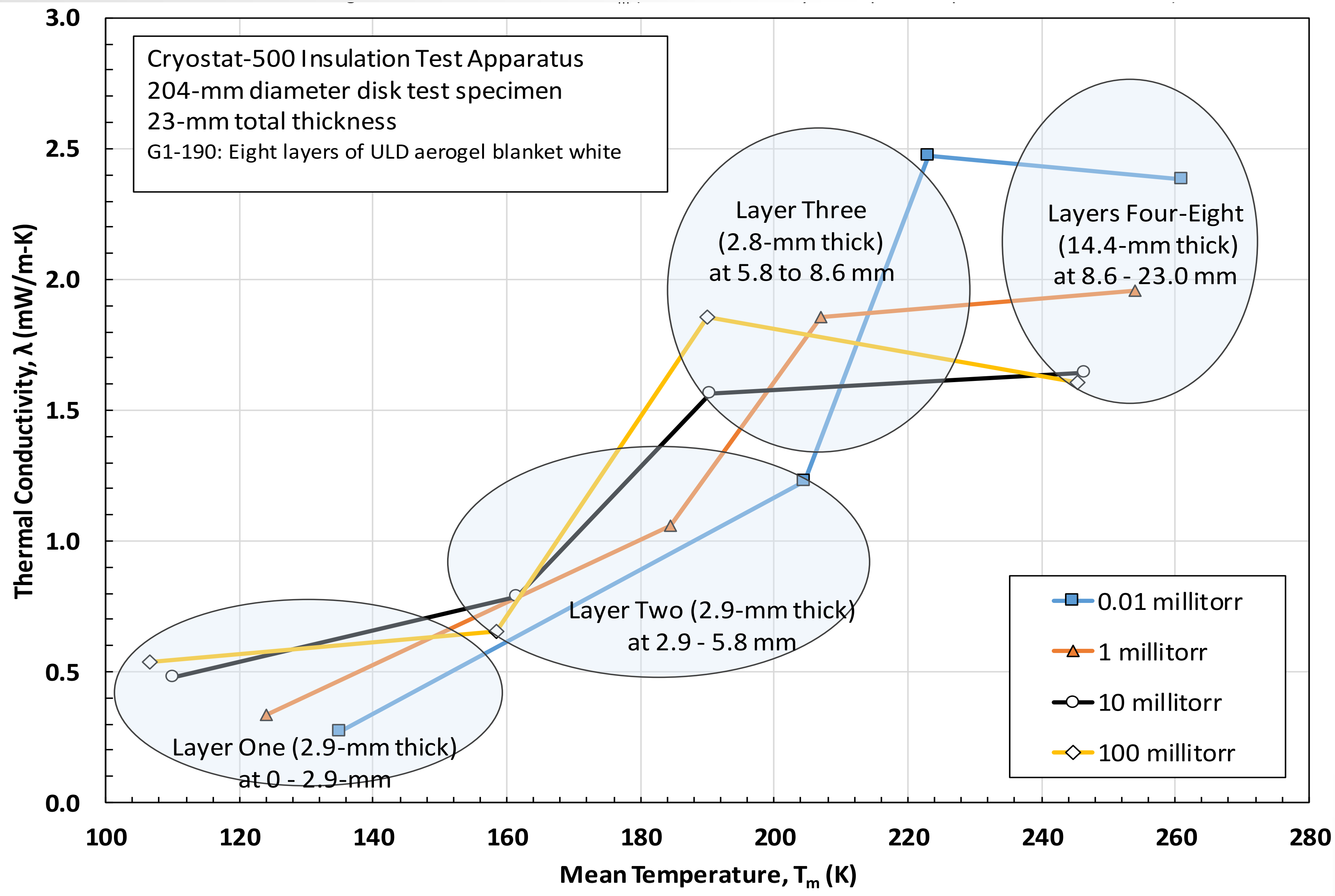
# LAMBDA CALCULATIONS FOR TEMPERATURE DEPENDENCE

- Intermediate temperature sensors provide a way to determine the temperature dependence of thermal conductivity (λ):
  - Within the two prescribed boundary temperatures, WBT and CBT
- The use of three intermediate temperature sensors creates four layers, numbered from one to four, from the cold side
- Basic nomenclature and equations:

| | |
|---|---|
| $Q = k_e * A_e * \Delta T/\Delta x$ | Fourier equation |
| $q = Q/A_e$ | constant (steady-state) |
| $q = q_1 = q_2 = q_3 = q_4 = \lambda_4 * \Delta T_4/\Delta x_4$ | and so forth |
| $T_m = (T_{colder} + T_{warmer})/2$ or $T_{m4} = (T_{c4} + T_{w4})/2$ | and so forth |

# INTERMEDIATE THERMAL CONDUCTIVITIES CALCULATED FOR G1-190 ULD AEROGEL WHITE






- Variation of lambda (λ) with mean temperature ($T_m$) for four different cold vacuum pressures
- ULD aerogel white
- Cryostat-500 test series G1-190



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# THERMAL PERFORMANCE ESTIMATES FOR DIFFERENT BOUNDARY TEMPERATURES

- Baseline heat flux ($q_{base}$) test data at the standard boundary temperatures of 293 K and 78 K
- Plus additional test data from the literature for MLI under high vacuum (<$10^{-5}$ torr) with warmer or colder boundary temperatures
- Estimation of the thermal performance for a specific layered system design is calculated using a warm boundary temperature factor ($b_w$) and a cold boundary temperature factor ($b_c$):

$$q_{design} = b_c * b_w * q_{base}$$

# BOUNDARY TEMPERATURE FACTORS



Increase in heat flux for increasing WBT (for MLI system with constant CBT = 78 K)

| WBT (K) | $\Delta$T | % increase, $\Delta$T | % increase, q | factor $b_w$ |
|---|---|---|---|---|
| 293 | 215 | baseline | baseline | 1.00 |
| 305 | 227 | 6 | 14 | 1.14 |
| 325 | 247 | 15 | 32 | 1.32 |
| 350 | 272 | 27 | 46 | 1.46 |

Decrease in heat flux for decreasing CBT (for MLI system with constant WBT = 300 K)

| CBT (K) | $\Delta$T | % decrease, $\Delta$T | % decrease, q | factor $b_c$ |
|---|---|---|---|---|
| 76 | 224 | baseline | baseline | 1.00 |
| 40 | 260 | 16 | 14* | 0.86 |
| 20 | 280 | 25 | 21 | 0.79 |
| 4 | 296 | 32 | 33 | 0.67 |

*Interpolated value

# EXAMPLE: ESTIMATE OF HEAT FLUX

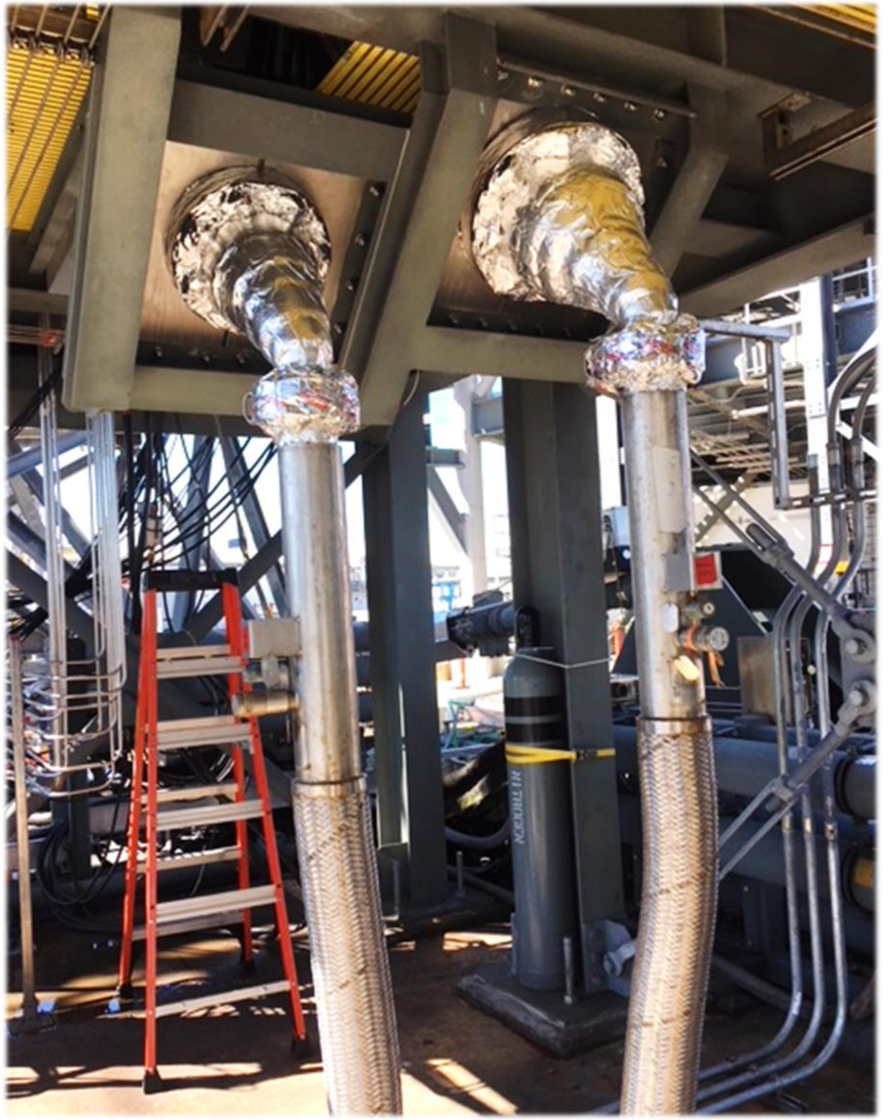
- For example, the heat flux estimate for a system operating at boundary temperatures of 325 K / 20 K is approximately the same thermal performance as the baseline of 293 K / 78 K:

$$q_{design}=1.32*0.79*q_{base} = 1.04*q_{base}$$

- Heat flux is proportional to the $\Delta T$ (and $T^4$ for the radiation portion), but the materials' heat transmission characteristics are changing with lower temperatures, combined with possible improvement of the level of vacuum

# LAUNCH EQUIPMENT TEST FACILITY

Space Launch System (SLS) cryogenic umbilical systems, LH2 piping and components





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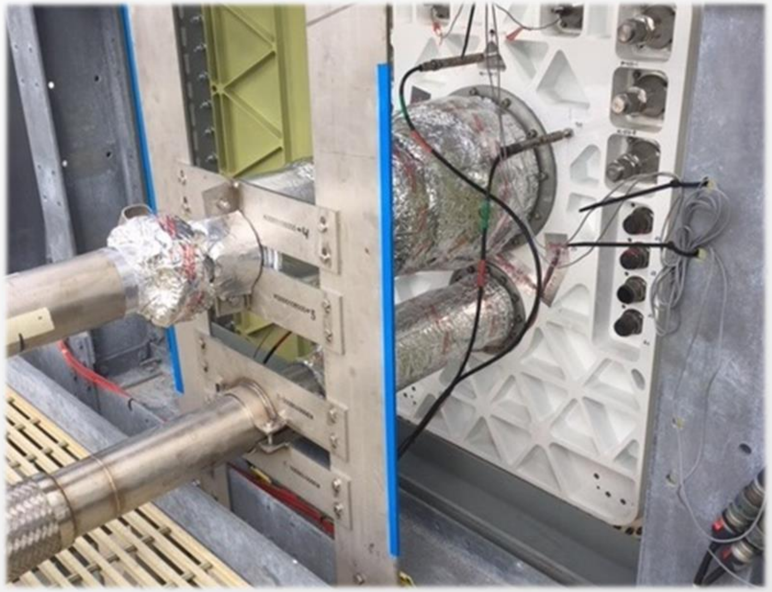
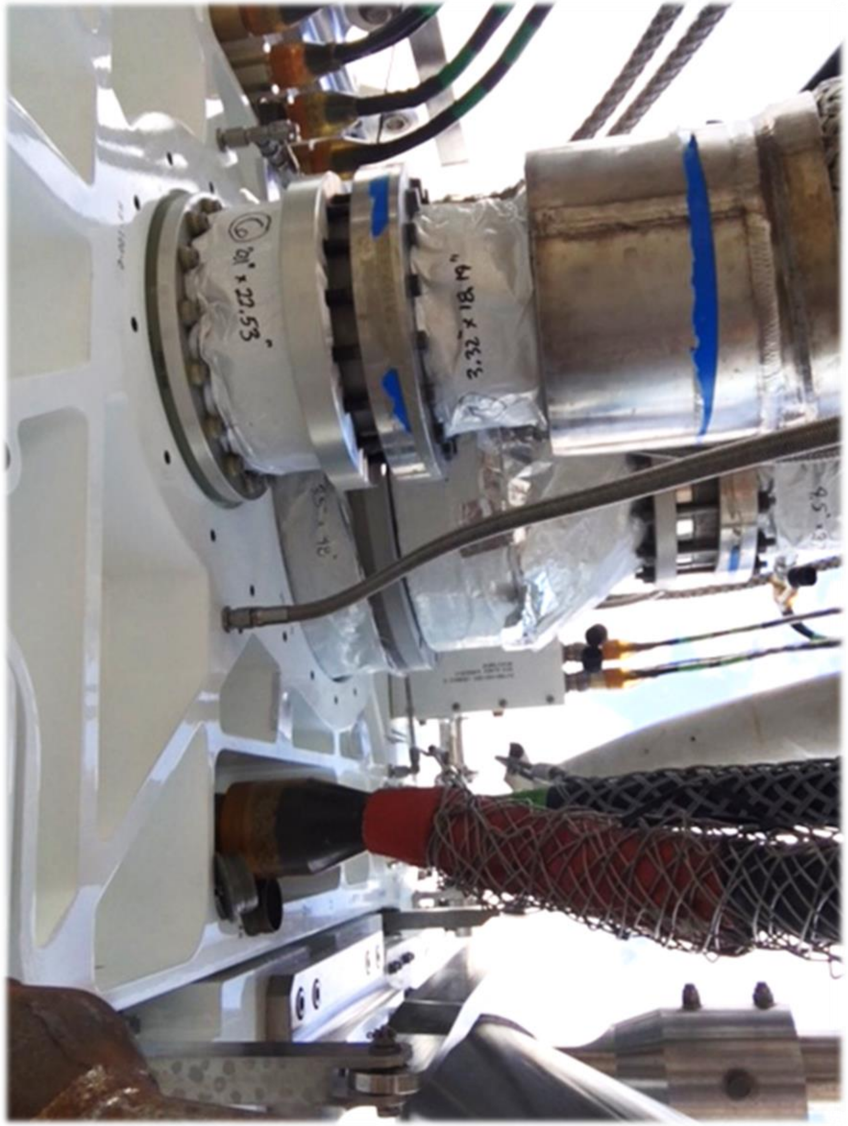


# CRYOFUEL UMBILICAL CONNECTION: LH2

Custom aerogel bulk-fill system (ground side) and LCX solution (flight side) successfully tested with multiple LH2 operations





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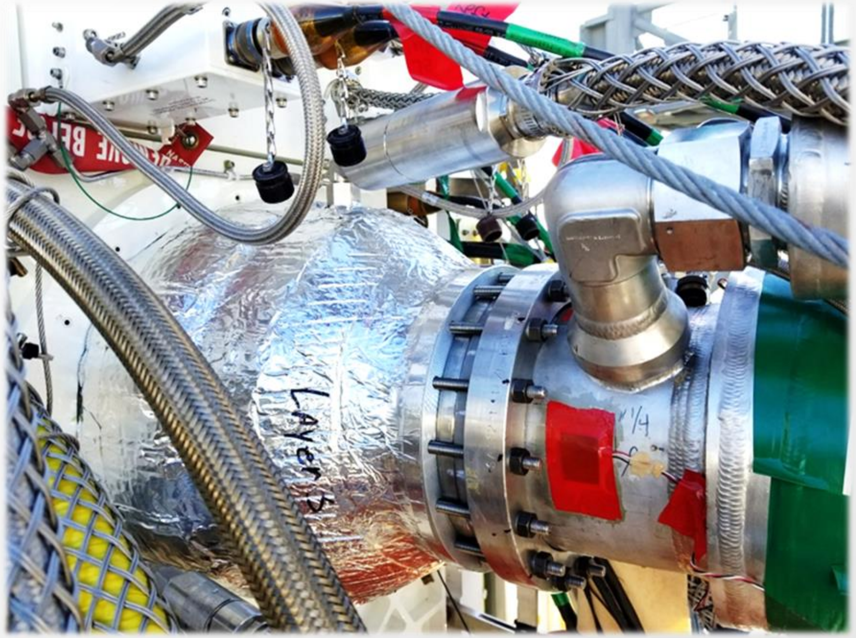
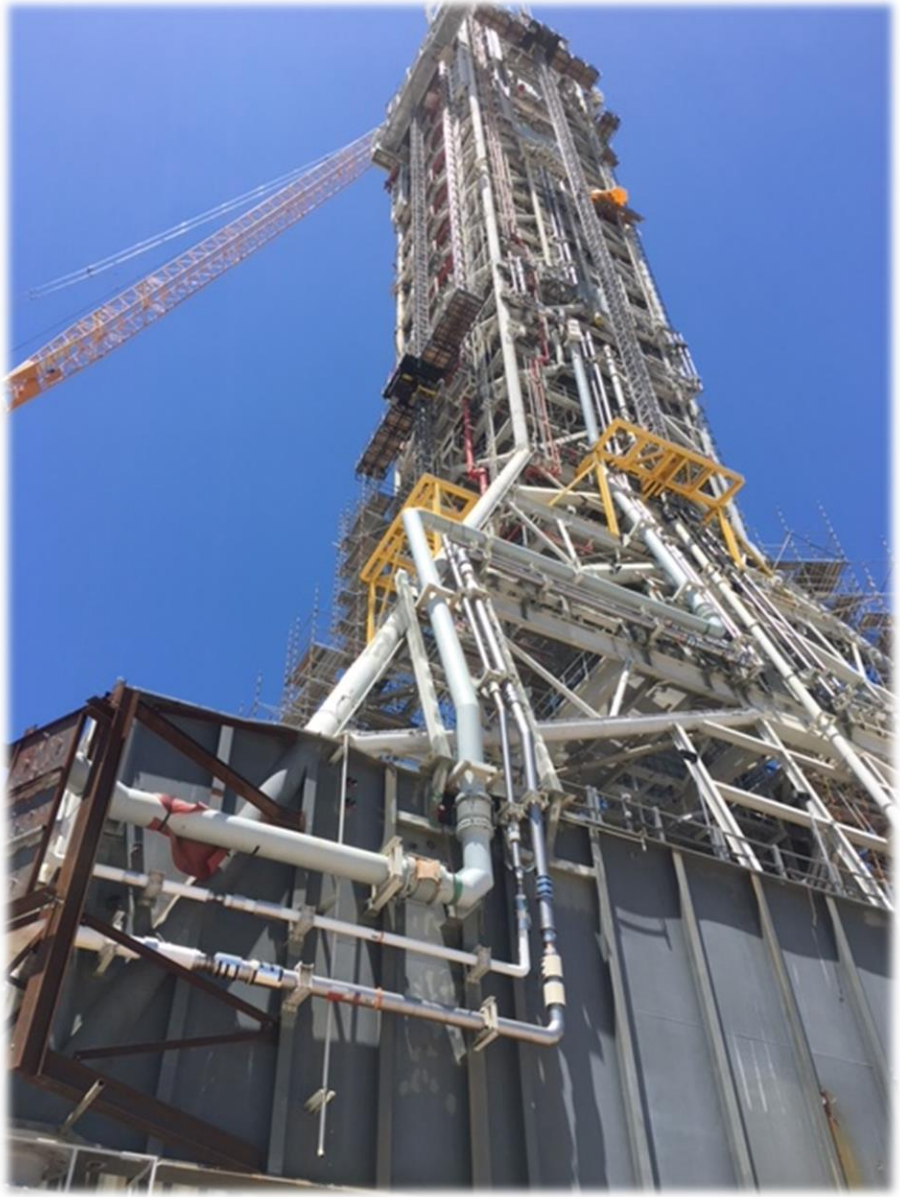


# CRYOFUEL UMBILICAL CONNECTION: LO2

Custom LCX solution on LO2 umbilical for Space Launch System (SLS) propellant loading system





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# FUTURE UPPER STAGE LAUNCH VEHICLE INSULATION

Aerogel-based layered composite insulation system for LH2 tank

- LCX variant under development to solve old problem of "external insulation" on cryogenic upper stages of launch vehicles for the keeping of liquid hydrogen (LH2)
- Enables function in all three wildly different environments:
  - **Ground** (moisture, liquid air formation)
  - **Flight** (aerodynamic forces)
  - **Space** (on-orbit, high-vacuum insulation)
- Lightweight, robust LCX addresses the triple problem in a synergetic approach
- Cryogenic-vacuum testing shows ~50 times better performance (lower heat flux) in vacuum compared to state-of-the-art foam



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# CONCLUSION

*Aerogel-Based Insulation Materials for Cryogenic Applications*

- Cryogenic-vacuum thermal performance of aerogel-based thermal insulation systems is provided for a variety of applications
- Field applications show unique thermo-economic performance advantages of aerogel systems when looking at the total picture and the reality of installation on complex hardware
- Aerogels include blanket composites, bulk-fill type, and layered systems with radiation shields
- Future aerogel materials under development can lead to further advances, enabling entirely new approaches and applications
- Different aerogel materials are commercially available today, proven in both vacuum and non-vacuum environments at temperatures from 4 K to 400 K

# THANK YOU

for your attention

Questions?